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Eemian–Weichselian Pleniglacial fluvial deposits in southern Poland (an example of the Vistula River valley in Kraków)

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A fragment of the middle terrace in the Vistula River valley, nearby the railway station in Kraków, is formed by fluvial channel and overbank deposits of the Prądnik River, which bear a record of various environments affected by changing climatic conditions. The sedimentary succession includes two complexes that differ in lithofacies. The older complex comprises fining-upward deposits (channel sand and gravelly sand with medium- and large-scale trough cross-stratification) and, less frequently, sand with planar cross-stratification overlain by silt with intercalations of biogenic deposits of abandoned channels. Vegetation accompanying the deposition of biogenic layers was typical of boreal coniferous forests, dominated by *Pinus sylvestris* with a small admixture of *Larix, Pinus cembra, Picea, Betula* and *Populus*. Periodically, the landscape passed into open areas overgrown by woody tundra. The complex developed as a result of activity of a meandering river under conditions of a moderately cool climate. The younger complex includes the sand lithofacies with horizontal stratification and low-angle cross-stratification, overlain by alternating sands and silts. The topmost part is represented by sands with large- and medium-scale planar cross-stratification. Lack of biogenic deposits and considerable amount of frosted quartz grains in alluvial sediments indicate aeolian processes of greater intensity, periglacial conditions and evolution towards a braided or transitional river. Pollen successions, absolute dating and studies of structural and textural features of the sediment suggest that the time of its deposition may be estimated at a range between the close of the Eemian Interglacial and the Weichselian Middle Pleniglacial (OIS 5e–OIS 3).

Key words: Eemian–Weichselian, river deposits, sedimentology, pollen analysis, climate change, southern Poland.

INTRODUCTION

Kraków is located in the borderland of several large morphostructural units: the Sandomierz (Subcarpathian) Basin, Outer Carpathians and Kraków Plateau (Fig. 1). Most of the city is situated within the Sandomierz Basin, a depression filled mainly with Middle Miocene claystones and mudstones with less frequent sandy sediments. The latitudinally oriented Vistula valley extends over a large area of the basin. The Outer Carpathians, separated by an easily recognized morphological edge and composed of flysch sandstones and shales (Jurassic–Lower Miocene), rise to the south. The Kraków Plateau, an extensive area composed of hard Upper Jurassic limestones with flint concretions, slopes down in several steps from the north. Eastwards, the plateau is covered mostly by Upper Cretaceous marls. All older rocks are locally overlain by Quaternary sediments of different origin and thickness.

Within the city, the major tributaries flow into the Vistula River: the left-bank Rudawa and Prądnik rivers, both draining the southern part of the Kraków Plateau and eroding the older Vistula River deposits, and the right-bank Wilga River, draining the Outer Carpathians. The lowest part of the valleys consists of a two-step floodplain. Upwards, in its northern part, the Vistula valley is marked by rising steps of terraces, sandy at the top, attaining the heights of 10–12 and 15–20 m and divided into several patches by left-bank tributaries of the Vistula River. One of these patches is referred to as the Prądnik River fan and its origin was dated to the Saalian Glaciation (Tyczyńska, 1968), Weichselian Glaciation (Setmajer, 1973), and then to the Weichselian Upper Pleniglacial (Rutkowski, 1987).

In the previously drilled boreholes, alluvial deposits were encountered in the Vistula valley near the "Kraków Główny" railway station. Their maximum thickness was nearly 27 m (Fig. 2). A construction excavation located west of the railway platforms exposed the upper part of section, nearly 12 m in thickness, composed of fluvial detrital sediments (silts, sands, gravels)

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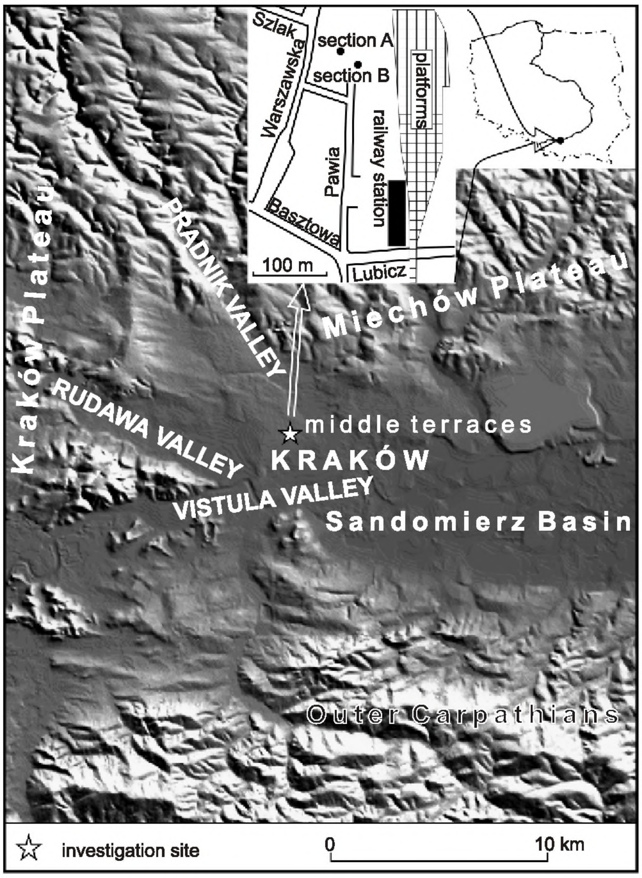


Fig.1. Location of the study area *versus* SRTM level 2 image

transported by the Prądnik to the Vistula valley, and biogenic deposits (peat; Fig. 2). Their top, within the excavation and its nearest surroundings, is elevated ca. 15–16 m above the present-day Vistula channel.

Presently, the Prądnik River is narrow, only locally exceeding 5 m in width, and flows in a bed straightened and largely channelized. The 18th and 19th century maps show a meandering channel pattern. The catchment covers an area of over 200 km^2 and the mean annual flows slightly exceed 1 m^3/s (Pociask-Karteczka, 1994).

The purpose of the study was to: (1) reconstruct the conditions of sediment deposition by the Prądnik in the Vistula valley, (2) reconstruct the climatic changes accompanying alluvial accumulation, and (3) identify the age of the sediments.

METHODS

The objectives of the study were achieved with the use of structural, textural, palynological and plant macroremain analyses and dating, applied for sediments exposed in the excavation in two sections. The investigations included vertical and lateral diversity of the sediments.

SEDIMENTOLOGICAL ANALYSIS

Description of sedimentary structures is based on codes proposed by Miall (1996), as modified by Zieliński (1995). Thickness intervals used to determine the scale of lithofacies were as follows: up to 6 cm – small-scale, 6–30 cm – medium-scale, and over 30 cm – large-scale (see Zieliński, 1998).

GRAIN-SIZE ANALYSIS

The sediment material for identification of textural features was taken only from sandy deposits, and subjected to dry grain-size analysis using a set of sieves for fractions between 2.0 and 0.063 mm in an interval of 0.5 phi. The results provided a basis to calculate the basic grain-size parameters (M_z, σ_1 and Sk_1), following Folk and Ward (1957), and to plot the cumulative curves on probability plots.

ROUNDING AND FROSTING OF QUARTZ GRAINS

Quartz grains of the 0.8–1.0 mm fraction from all samples were subjected to analyses of surface rounding and frosting following Cailleux (1942), as modified by Goździk (1980, 1995) and Mycielska-Dowgiałło and Woronko (1998). The analysis compiles the type of grain surface, indicating the environment of sediment transport or of *in situ* weathering, with the rounding degree, presented according to a 9 degree scale (Krumbein, 1941). Seven types of quartz grain surfaces, bearing a record of

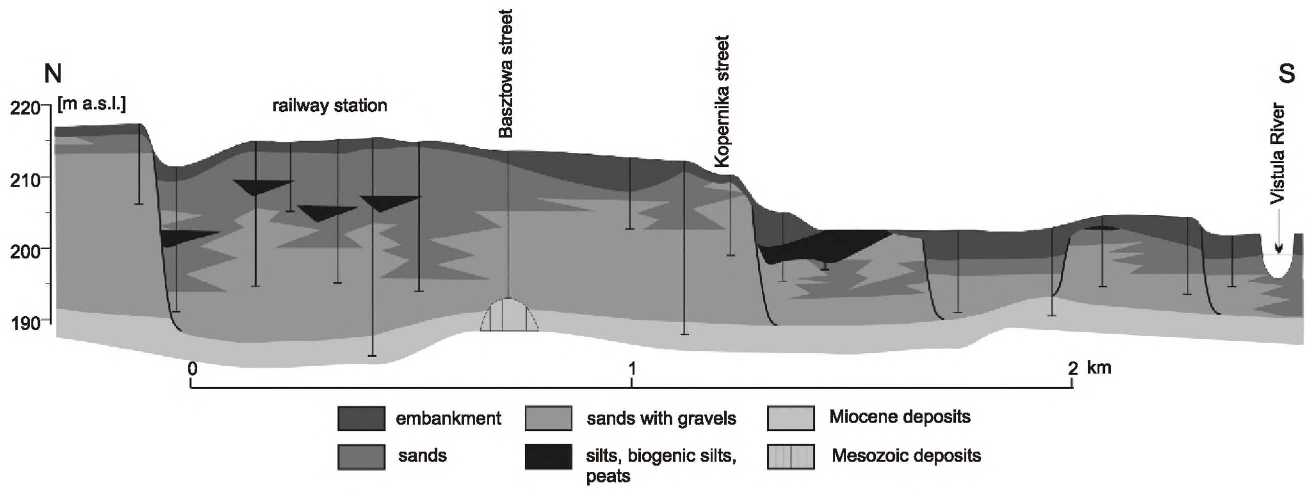


Fig. 2. Geological cross-section along part of the middle terrace of the Prądnik River

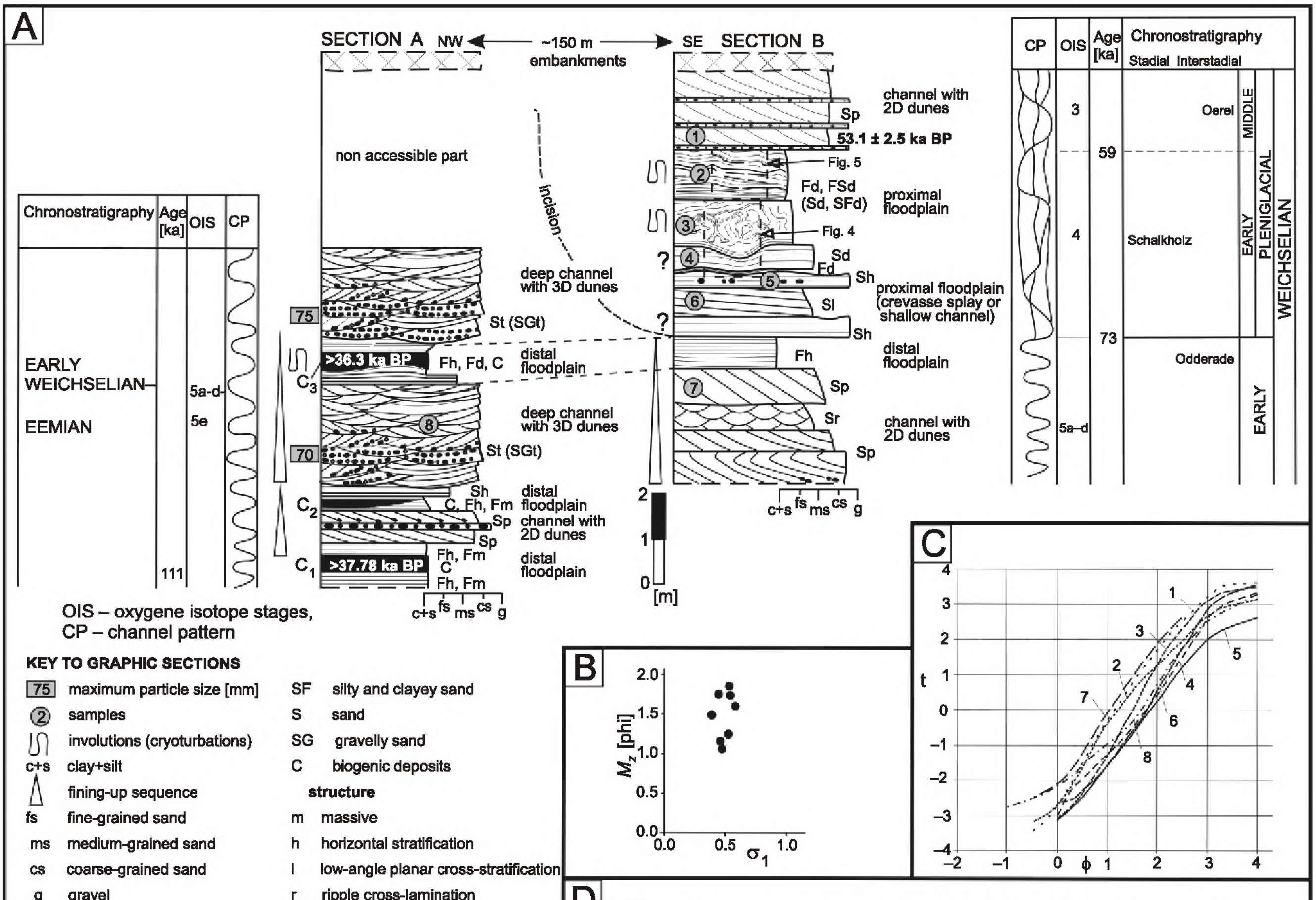
the last process that shaped their microrelief, were distinguished in the sandy fraction:

- RM – rounded and frosted grains (the rounding degree 0.7–0.9), representing an aeolian environment. High level of surface rounding results from long-lasting abrasion (Mycielska-Dowgiałło, 2001);
- EM/RM – grains of frosted edges and corners, intermediate rounding degree (0.3–0.6) and surface affected by abrasion for a relatively short time in an aeolian environment;
- EL – rounded and shiny grains (0.7–0.9), formed in aquatic environments (including fluvial and high-energy beach environments; Woronko and Ostrowska, 2009; Woronko et al., 2013);
- EM/EL – shiny grains of an intermediate rounding degree (0.3–0.6), representing aquatic environments;
- NU – completely fresh all grain surfaces, with no traces of chemical weathering or abrasion; 0.1–0.2, affected by damages in a glacial environment (e.g., Gomez and Small, 1983; Mahaney, 2002) or by weathering, e.g. frost action (Woronko and Hoch, 2011; Woronko, 2012a);
- C – broken, with at least a 30% loss (Goździk, 1995) of the original grain surface. Only the broken surface is fresh and has sharp edges, not marked by traces of post-sedimentation processes;
- OTHER – grains of different rounding degrees, with a surface formed by strong chemical and/or mechanical weathering and not affected by abrasion.

For the same samples, percentage values of quartz grains were calculated, providing an indirect measurement of the duration of abrasion processes (Woronko, 2001; Mycielska-Dowgiałło and Woronko, 2004a, b).

PALAEOBOTANICAL STUDIES

Biogenic deposits were subjected to pollen and plant macroremain analyses. Samples for palynological examinations were taken in several-cm intervals from three sediment layers: C1 (9 samples), C2 (6 samples), and C3 (10 samples; Fig. 3). Single pilot samples were also collected from sands separating these layers. Chemical preparation of samples, with the volume of 1 cm^3, followed the modified procedure of



Sample	M_z	σ_1	Sk_1	NU [%]	EL [%]	RM [%]	EM/EL [%]	EM/RM [%]	OTHER [%]	C [%]
1	1.1560	0.4608	0.0250	0.0	0.0	4.1	1.7	91.7	0.0	2.5
2	1.2454	0.5271	0.1456	0.0	0.0	0.9	35.9	24.5	4.7	34.0
3	1.4893	0.3878	–0.0128	–	–	–	–	–	–	–
4	1.7396	0.5449	–0.1293	0.0	0.0	3.8	0.8	94.7	0.0	0.8
5	1.8538	0.5341	0.0070	0.0	0.0	15.0	2.6	80.8	0.8	0.8
6	1.7510	0.4450	–0.0947	0.0	0.0	2.9	2.9	90.4	0.7	2.9
7	1.0612	0.4716	0.0321	–	–	–	–	–	–	–
8	1.5989	0.5826	–0.2721	1.6	0.0	0.0	36.0	53.6	6.4	2.4

Fig. 3A – sedimentological sections related to chronostratigraphy, isotope stages and channel pattern; B – relationship between mean grain diameter (M_z) and standard deviation (σ_1); C – granulation; D – rounding and frosting (chronostratigraphy, oxygen isotope stages, ages after Hammen et al., 1967; Martinson et al., 1987; Behre and Plicht, 1992; Dansgaard et al., 1993)

NU, EL, RM, EM/EL, EM/RM and OTHER are explained in the text

Erdtman's acetolysis (Berglund and Ralska-Jasiewiczowa, 1986). In each sample, an average of 600 grains of trees and shrubs were identified. This figure included terrestrial, aquatic and swamp pollen as well as spores. Percentage values of sporomorphs were calculated with reference to the sum of pollen count for trees and shrubs (AP) and herbaceous plants (NAP), excluding local taxa. For swamp, aquatic and spore plants, the total sum was each time increased by the counts of remains of particular taxa. Morphological pollen types were determined with the use of keys of Moore et al. (1991) and Beug (2004), and the reference collection of the W. Szafer Institute of Botany, PAS, in Kraków. Percentage pollen diagrams were plotted with the *POLPAL* software for Windows. Distinction of Pollen Assemblage Zones (PAZs) was based on the *ConSLink* analysis (Walanus and Nalepka, 1999; Nalepka and Walanus, 2003).

The material for plant macroremain analysis was sampled in correlation with that for palynological studies. Samples, with the volume of ca. 200 ml, were macerated in 10% KOH and sieved on sieves with the mesh diameter of 0.2 mm. Remains of plants were selected for taxonomic identifications. Carpological studies and determination of wood and charcoal were performed by Zofia Tomczyńska.

ABSOLUTE AGE DATING

Radiocarbon and OSL absolute ages of biogenic and clastic sediments were determined at the GADAM Centre (Gliwice Absolute Dating Methods Centre, Silesian University of Technology, Poland). For conventional radiocarbon dating, two samples (ca. 100 g each) of strongly decomposed peat were taken from the middle of C1 and C3 layers. For OSL datings, one sample from the sand layer was collected (Fig. 3).

RESEARCH RESULTS OF DEPOSITS

The study covers one complete section (section B – Fig. 3) and the lower part of the second section (section A – Fig. 3). The sections are separated from each other by a large artificial slump.

DETRITAL DEPOSITS

Section A (Fig. 3A) is dominated by medium- and coarse-grained (nearly 50% of total thickness), well-sorted sand (Fig. 3D). The content of gravelly sand, silty sand and peat is subordinate.

The section is dominated by the sand and gravelly sand lithofacies with medium- and large-scale trough cross-stratification (St and SGt – Fig. 3A). Gravel grains are represented mostly by Jurassic limestones. A small proportion of Carpathian cobbles were noted in the lowermost part of the section. Sand with planar cross-stratification (Sp) and horizontal stratification (Sh) is the secondary lithofacies.The following cycles have been identified: St(SGt) → Fh(Fm, C) or Sp → Fh(Fm, C). The sand lithofacies attains ca. 2 m in thickness and is overlain by fine-grained deposits, usually forming sheet-like bodies of massive structure (Fm) or horizontal lamination (Fh). Each cycle includes peat (C) in its upper part (Fig 3A).

Results of rounding and frosting analyses performed on quartz grains from section A show that lithofacies St and SGt (sample no. 8) are dominated by EM/RM grains, moderately rounded, which results from abrasion in an aeolian environment. Their proportion is up to 53.6% (Fig. 3D). EM/EL grains, representing an aquatic environment, are abundant as well (36.0%). "Other" (6.4%) and broken grains (2.4%) occur in minor amounts (<10%). Fresh grains (NU) are also observed, in the frequency of 1.6% (Fig. 3D).

Section B (Fig. 3A) is dominated by medium-grained sand (Fig. 3B, D). In the lowermost and uppermost parts of section B, sand with large- and medium-scale planar cross-stratification (Sp) is the main lithofacies. In the middle part the sand lithofacies, Sh and occasionally Sl are present. The silt, sandy silt and silty sand lithofacies (Fd, FSd and SFd) are also found in relatively high proportions. Large-scale irregular involutions (load structures) occur in few silty and silty-sandy horizons, accounting for nearly 25% of section B. These large-scale structures, >60 cm in amplitude, represent fold involutions of type 2 and 3, following Vandenberghe (2007; Fig. 4). The intensity of disturbances decreases upwards; the folds show a maximum amplitude slightly exceeding 30 cm (type 1 according to Vandenberghe, 2007; Fig. 5).

Results of grain-size analysis indicate that the sediments are well-sorted (σ_1 from 0.38 to 0.58) and characterized by mean grain diameter (M_z) varying between 1.85 and 1.06 phi and skewness (Sk_1) ranging from –0.27 to 0.14 (Fig. 3C, D). According to rounding and frosting analyses of quartz grain surface, following Cailleux (1942) with later modifications, section B (samples nos. 1, 3–5) is noticeably dominated by grains processed in an aeolian environment. The sum of RM and EM/RM grains amounts to 93.3–98.5% (Fig. 3D), however generally (90.4–94.7% of grains) only edges and corners are affected by aeolian processing. A bed comprising lithofacies Sh with single gravels is the only one including 15.0% of RM grains, typified by a very high level of rounding and completely frosted surface (sample no. 5; Fig. 3D).

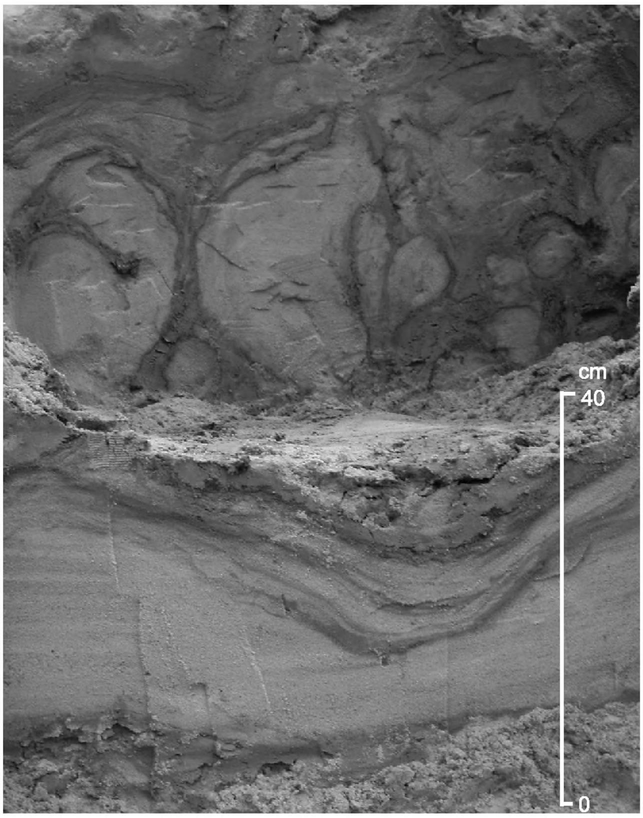


Fig. 4. Irregular cryoturbations in section B

Fig. 5. Fold deformations in section B

Paddle is 30 cm high

Sample no. 2 is worth consideration as well because the grains from an aeolian environment (sum of RM and EM/RM) attain a frequency of 25.4%. Grains with surfaces shaped mainly in an aquatic environment (EM/EL) and broken grains (C) are also found. The proportion of the latter is as much as 34%, while in the other samples, it does not exceed 3% (Fig. 3D). They were formed as a result of destruction of grains representing both aeolian and aquatic environment. Such a variety of particle types indicates that they are in a secondary deposit, and the older sediments were derived from different sources (Woronko, 2012a).

BIOGENIC DEPOSITS

Biogenic deposits, represented by dark brown to almost black peat (layers C1 and C2) decomposed in 60–70%, and dark brown sedge peat (layer C3) decomposed in 50–60%, form three layers (C1, C2, C3 – Fig. 3A). They are interbedding the silt (Fh and Fm lithofacies) at the top part of fining-upward cycles. The topmost layer displayed slight involutions (small-scale folded structures – type 1 according to Vandenberghe, 2007).

PALAEOBOTANICAL INVESTIGATIONS

Pollen spectra of layer C1 (Figs. 3A and 6) represent communities of boreal coniferous forests dominated by Scots pine (*Pinus sylvestris*) with a small admixture of spruce (*Picea abies*), larch (*Larix*), stone pine (*Pinus cembra*), poplar (*Populus*) and birch (*Betula*). As larch is recorded in high amounts, they most likely inhabited immediate surroundings of the site of sediment sampling. Ecological requirements of *Larix* as well as low pollen production and its limited dispersal (Jankovská and Pokorný, 2008) indicate local occurrence of patches of forest communities with low-density tree stands. Their ground layer was overgrown by *Vaccinium*, *Lycopodium annotinum*, *Pteridium aquilinum, Dryopteris*, and other ferns. Plants representing Poaceae and less frequently *Artemisia*, Cichorioideae, *Ranunculus*, Rubiaceae and Apiaceae were

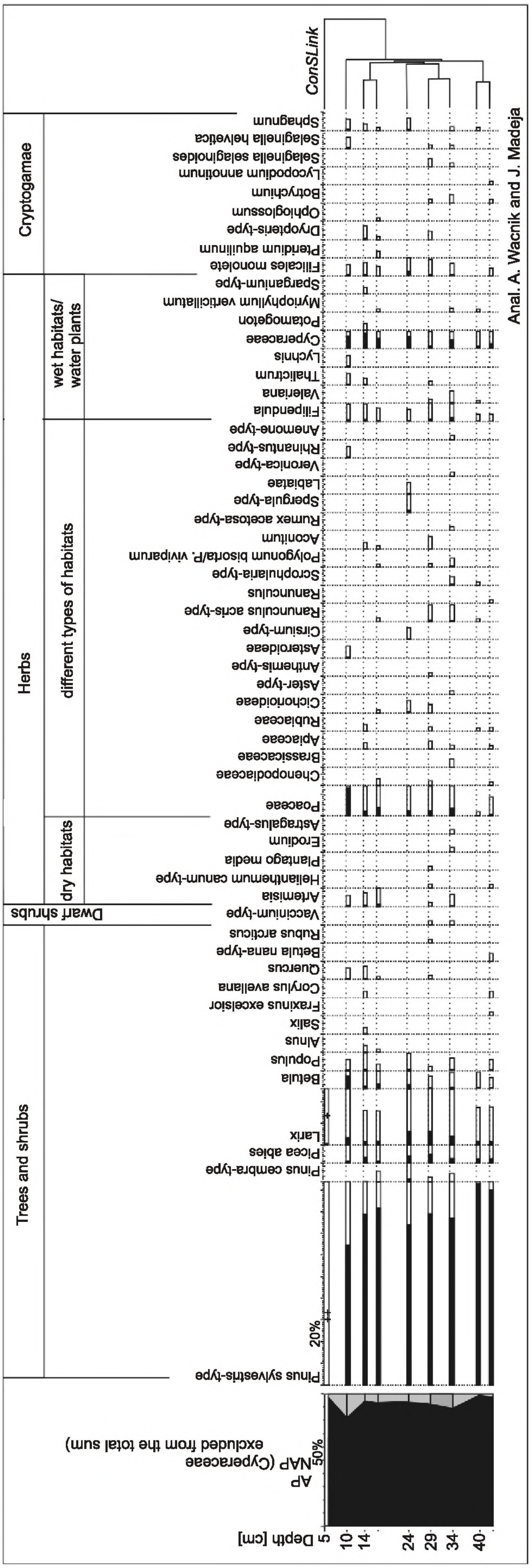


Fig. 6. Pollen diagram from biogenic deposits, layer C1

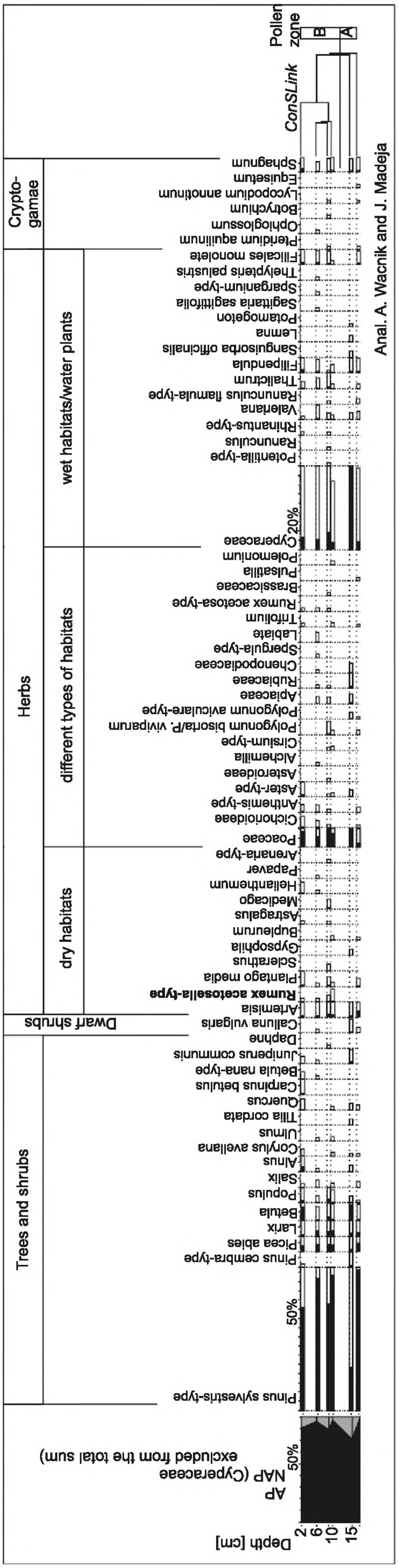


Fig. 7. Pollen diagram from biogenic deposits, layer C2

present in the ground layer and woodless areas. Relatively high amounts of Cyperaceae and *Filipendula* pollen, as well as the presence of *Valeriana*, *Thalictrum*, *Lychnis*, and *Sphagnum*, confirm the functioning of boggy, locally peaty habitats, occasionally including *Betula nana*. Humid grasslands were composed of *Ophioglossum* and *Botrychium*, while exposed grounds were covered by clubmosses (*Selaginella selaginoides* and *S. helvetica*). Periodically, waters of the basin remained open, allowing for the development of aquatic taxa: *Potamogeton*, *Sparganium* and *Myriophyllum verticillatum*.

Pollen analysis performed for the subsequent layer (C2 – Figs. 3A and 7) indicates a similar type of vegetation during the accumulation of organic sediments. The site was surrounded by boreal coniferous forests with *Pinus sylvestris*, admixture of *Larix* and single trees of *Picea abies*, *Pinus cembra, Populus*, *Salix* and *Betula.* In dry habitats, the shrub layer was overgrown by *Daphne* and *Juniperus*, while in wetlands, by *Betula nana.* Herbaceous vegetation was more abundant, possibly due to an increase in the surface of nearby woodless areas. Pollen of plants typical for dry habitats, such as *Helianthemum, Scleranthus, Artemisia*, *Rumex acetosella*-type and *Plantago media*, was found in minor amounts. Taxa requiring fresh and humid grounds were recorded more frequently and included mainly Poaceae, *Rumex acetosa* and Cichorioideae as well as plants representing *Aster* and *Anthemis.* One sample was marked by a very abundant occurrence of sedges (such as *Cyperis fuscus* and *Scirpus sylvaticus*, determined from macroremains), resulting from the increasing ground humidity. The presence of numerous Cyperaceae as well as *Betula nana*, *Thalictrum flavum, Filipendula, Valeriana*, *Ranunculus flammula*, *Polemonium, Sanguisorba officinalis*, *Thelypteris palustris, Sphagnum, Lemna, Potamogeton* and *Sagittaria sagittifolia* confirms the existence of boggy and peaty areas, periodically covered by open waters.

Layer C3 (Figs. 3A, 8 and 9) is marked by strongly decomposed sedge peat deposited in a shallow basin. The taxonomic composition of plant macroremains indicates the dominance of Cyperaceae, including genera such as *Carex* (*C. dioica, C. stricta, C. limosa, C. leporina, C. arenaria, C. canescens, C. rostrata, C. pseudocyperus*) and *Scirpus* (*S. tabernaemontani*, *S. lacustris*) were identified. *Eleocharis palustris*, *Rynchospora alba*, *Poa* sp. and *Epilobium palustre* (Fig. 9). The results of pollen analysis show a dual palynological record (Fig. 8). Spectra from the depth interval of 17–33 cm (zone C3a, Fig. 8) were very abundant in herbaceous plants, sedges and grasses. Vegetation of humid, boggy and aquatic habitats provides evidence for the development of a very shallow basin, with periodically opened water. Patches with *Sphagnum*, *Drosera intermedia* and *Empetrum* occurred locally. Shrubs of *Betula nana* appeared occasionally. Slightly drier areas were overgrown by *Filipendula*, *Valeriana officinalis*, *Veronica serphyllifolia* and *Cirsium*, while dry habitats, by *Juniperus*, *Hippophaë rhamnoides*, *Calluna vulgaris*, *Artemisia*, Chenopodiaceae, *Achillea millefolium, Silene* and *Gypsophila*. A numerous group of plants, like Poaceae, Apiaceae, Cichorioideae and *Aster,* was associated with various habitats.

The surroundings were occupied by pine forests with an admixture of spruce, stone pine and larch. The ground layer was overgrown by *Juniperus*. This zone is characterized by the highest proportion of birch. It inhabited both coniferous forests and the shore of the basin, where it was accompanied by single specimens of *Salix, Cornus sanguinea*, and possibly *Alnus*, *Populus* and *Corylus avellana*. The presence of *Betula*, *Salix* and *Cornus sanguinea* was confirmed also by the identification of their macroremains (Fig. 9). Infrequent pollen grains of *Ulmus*, *Tilia cordata* and *Quercus* were most likely carried in a

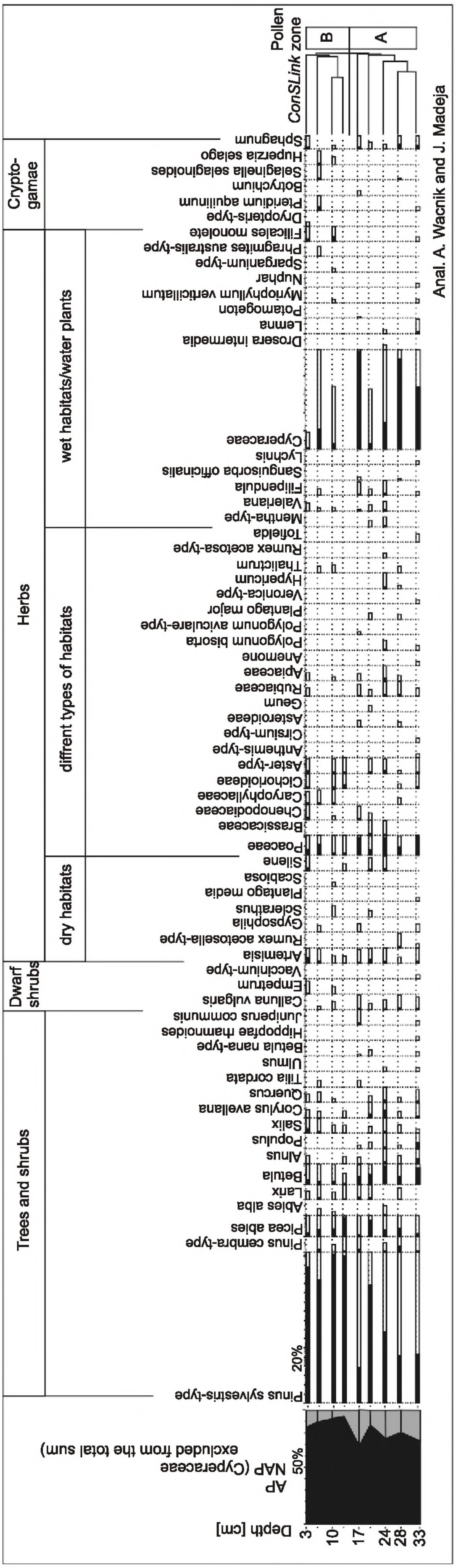


Fig. 8. Pollen diagram from biogenic deposits, layer C3

long-distance transport or redeposited. The presence of single particles of *Quercus* charcoal should be considered as an effect of redeposition, though in the lithology of this section, no mineral layers was observed, suggesting a higher input of older allochthonous matter. In this area, woody tundra, locally developed on grounds of high humidity, may have been the dominant plant formation.

Zone C3b (3–17 cm from the top, Fig. 8) bears a record of re-expansion of boreal coniferous forests, dominated by Scots pine with a small admixture of spruce and larch, which possibly resulted from a decrease in humidity. This observation was also confirmed by the presence of a 4 cm long *Larix/Picea* wood fragment at the top of the layer. *Pinus sylvestris* showed an increase in pollen frequency and was still accompanied by a high admixture of *Picea*. *Larix* occurred regularly, while *Betula* decreased its proportion. The values of herbaceous plants, particularly Cyperaceae and Poaceae, were strongly reduced, as confirmed by the results of macroremain analysis. No remains of aquatic plants were noticed, except for a single pollen grain of *Myriophyllum verticillatum*. Swamp plants were represented by *Phragmites australis*, *Typha angustifolia* and *Carex stricta*.

INTERPRETATION OF DEPOSITIONAL ENVIRONMENTS

The sediments examined are part of the terrace of the Prądnik River that drains the Kraków Upland in the north. It is evidenced by the petrographic composition of the gravels, dominated by Jurassic limestones. Only the admixture of Carpathian sandstones, found in the lowest part of the investigated outcrop, may indicate a slight influence of the Vistula or Rudawa rivers (cf. Rutkowski and Sokołowski, 1984).

Quartz grains in section B (except in sample no. 2) are very homogeneous in their type and are clearly dominated by grains affected by processing in an aeolian environment (RM and EM/RM types – over 95%; Fig. 3A, D). It evidences the importance of aeolian processes occurring in the environment during accumulation of the series. In Kraków, similar amounts of this grain type were recorded in deposits of the lower terrace and originate in the Weichselian Late Pleniglacial (Sokołowski et al., 2008). The deposition of lithofacies Sh and Sl overlying the silt sediments (section B – samples nos. 1–6) was preceded by slight incisions visible in some roof parts of these silt sediments. After the incisions, an abundant supply of aeolian sand to the river system may show its changes from meandering to sandy braided.

Nevertheless, it should be emphasized that traces of aeolian processes are easily recognized only at the edges and corners of grains, therefore they were either subject to abrasion for a relatively short time or the sediments were transported over a short distance (Mycielska-Dowgiałło, 1993; Woronko, 2001, 2012a). The slight increase in the proportion of aeolian grains, mainly of the RM type, observed upwards section B, is likely to evidence the synchronous occurrence of aeolian processes and accumulation of the examined deposits (Goździk, 2001; Woronko, 2012a). The cooling caused an increase in bedload and a tendency to braiding of the river. In the bottom of the valley, aggradation has occurred.

The deposits represent various fluvial subenvironments. Lithofacies St and SGt represent migration of 3D (lunate or linguoid) dunes and indicate deeper channel zones, whereas lithofacies Sp represents 2D (straight-crested) dunes or small transverse bars, being associated with straight and shallower inter-meander segments (McGowen and Garner, 1970; Jack-

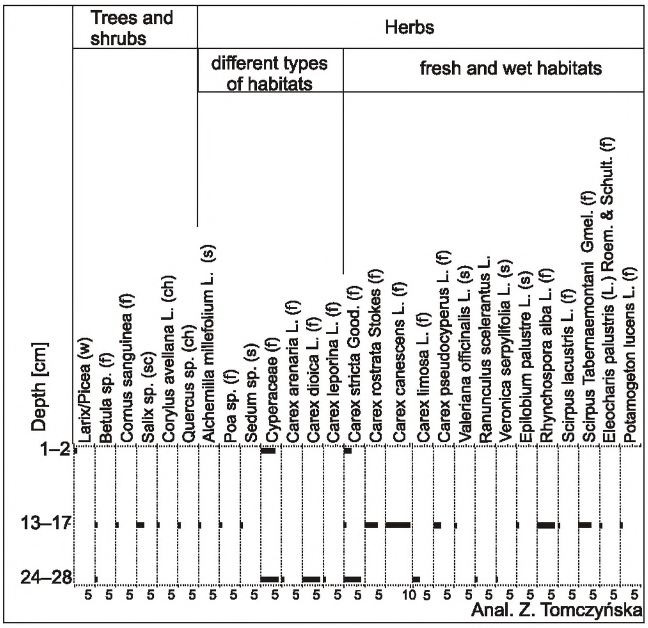


Fig. 9. Diagram of plant macrofossils from layer C3

ch – charcoal particles, f – fruits, s – seeds, sc – scales, w – wood fragment

son, 1976; Stewart, 1981; Bridge and Gordon, 1985). Lithofacies Sh and Sl are likely to indicate the presence of very shallow channels with plane-bed morphology and low relief bars, however, may be also linked to crevasse splays (cf. Teisseyre, 1988; Gębica and Sokołowski, 2001). Fine-grained lithofacies (Fh and Fm) represent the distal part of floodplain and, if peat occurs, represents abandoned channels. Deposits of the proximal floodplain are represented by sandy-silty alternations (lithofacies Fd, FSd, Sd, and SFd – Fig. 3A).

The sedimentation, particularly in the lower part, should be attributed to a meandering river system. This conclusion can be supported by following factors: (1) considerable frequency (about 50%) of fine-grained lithofacies (Fh, Fm), biogenic deposits (peat) and sandy-silty alternations, (2) the occurrence of fining upward cycles St(SGt) → Fh(Fm, C) or Sp → Fh(Fm, C) include the succession of: channel filling → channel abandoning, (3) the occurrence of peat (abandonment stage) indicate boreal coniferous forests and periodically woody tundra and (4) relatively inconsiderable content of aeolian grains.

In the middle and upper parts of the succession (section B), biogenic deposits are absent. A high proportion of aeolian grains and the presence of lithofacies Sh and Sl (plane bed and low relief bars) may suggest passing into a transitional (threshold-type) river or into a sandy braided river.

CHRONOSTRATIGRAPHY AND RIVER DEVELOPMENT IN RELATION TO CLIMATE AND ENVIRONMENTAL CHANGE

EEMIAN AND WEICHSELIAN EARLY GLACIAL

ENVIRONMENTAL CONDITIONS

The investigated sections (layers C1, C2 and C3b; Figs. 3, 6–9) bear a record of tree stands composed mainly of Scots pine with a small admixture of larch, stone pine, spruce, poplar and birch (Table 1). The reconstructed vegetation shows the dominance of boreal coniferous forest. Zone C3a is the only one marked by the development of woody tundra vegetation,

Table 1

Chronostratigraphy and description of the pollen assemblage from the Kraków railway station

Chronostratigraphy (Behre and Lade, 1986)	Layer	Results of pollen analysis
Eemian–Weichselian Early Glacial	C3	71 taxa were identified from pollen and spores. Percentage values of trees attain an average of ca. 50% at the basal part and increase to ca. 90% in the top part. *Pinus sylvestris* is dominant, with a frequency between 20 and 81% at the top. Continuous curve of *Picea* (up to 10.6%). High proportion of *Betula*, amounting to 10% at the base, shows a decreasing trend accompanied by falling values of *Populus*, *Corylus*, *Quercus*, *Alnus*, and herbaceous plants. Nearly continuous presence of *Pinus cembra*-type and *Larix*. Single pollen grains of shrubs: *Juniperus*, *Betula nana*-type and *Hippophaë*. Dwarf shrubs are represented by a nearly continuous curve for *Calluna* and single records of *Empetrum* and *Vaccinium*. Highest Cyperaceae values (up to 53%) are characteristic for the zone. Stable, several-percent high frequency of Poaceae (up to 10%). Constant occurrence of *Artemisia* (up to 3.3%). Pollen of *Aster*-type, Cichorioideae, Chenopodiaceae, *Thalictrum*, Apiaceae, *Valeriana*, *Silene*, and *Gypsophila* recorded several times. Greater diversity of aquatic and swamp plants, with infrequent *Lemna*, *Nuphar*, *Sparganium*-type, *Potamogeton*, *Myriophyllum verticilatum*-type, and *Phragmites*. *Sphagnum* and *Drosera intermedia* found at the basal part. Spores of *Pteridium aquilinum*, *Selaginella selaginoides*, *Huperzia selago*, *Filicales monolete* and *Dryopteris*-type mainly in top samples.
	C2	74 taxa were identified. Spectra dominated by AP pollen, particularly of *Pinus sylvestris* (max. 75%), accompanied by a constant, several-percent high content of *Picea* (up to 4.6%), *Larix* (up to 3.3%) and *Betula* (up to 8.7%). Continuous curve of *Populus*. Taxa such as *Salix*, *Alnus*, *Quercus*, *Pinus cembra*-type and *Corylus avellana* recorded several times. Shrubs represented by *Juniperus*, *Betula nana*-type and *Daphne*. Within herbaceous plants, culmination of Cyperaceae (max. 44.3%) at the beginning of the zone. Frequency of Poaceae stable, attains max. 9.7%. Continuous curves for *Artemisia*, *Filipendula* and *Valeriana* and regularly recorded *Plantago media*-type, *Rumex acetosella*-type, *Aster*-type, *Anthemis*-type, *Thalictrum*, Rubiaceae and Apiaceae. Aquatic and swamp plants recorded as single specimens (*Lemna*, *Potamogeton*, *Sparganium*-type, *Sagittaria sagittifolia*, *Thelypteris palustris*). Spores of *Filicales monolete* and *Sphagnum* constantly present in spectra, occasionally accompanied by *Lycopodium annotinum*, *Ophioglossum* and *Pteridium*.
	C1	61 taxa were identified. Total dominance of AP pollen. Very high amounts of *Pinus sylvestris* (up to 93%). Abundant *Larix* (up to 6.4%). Constant, except for the top sample, occurrence of *Picea* (max. 4.4%) and *Betula* (max. 6%). *Populus*, *Pinus cembra*-type and *Quercus* recorded several times. Single pollen grains of *Betula nana*-type and *Rubus arcticus*-type. Relatively infrequent appearance of NAP taxa, with Poaceae, Cyperaceae and *Filipendula* as most important ones. *Artemisia*, Apiaceae, Rubiaceae, *Polygonum bistorta*, *Ranunculus acris*-type, and *Aconitum* determined several times. Pollen of aquatic plants found occasionally. Presence of spores of, i.a., Filicales monolete, *Selaginella selaginoides*, *Selaginella helvetica*, *Dryopteris*-type, *Ophioglossum* and *Sphagnum*.

characterized by the coexistence of cold climate indicators, such as *Pinus cembra*, *Larix*, *Betula nana, Rubus arcticus* and *Selaginella selaginoides,* and infrequent remains of plants with higher temperature requirements, i.e. *Myriophyllum verticillatum*, *Nuphar*, *Pteridium aquilinum*, *Sanguisorba officinalis* and *Drosera intermedia* (Table 1). Its sediments were deposited in an increasingly humid habitat. Pollen succession from the Świnna Poręba site (Western Outer Carpathians), Brörup or older in age (Bińka and Grzybowski, 2002), revealed similarities in a general character of vegetation with a high frequency of *Pinus sylvestris*, *Picea*, *Larix* in local woods, but also differences: e.g. more open woodland communities with pine, higher representation of *Alnus*, regular presence of *Picea omoricoides* type and *Bruckenthallia spiculifolia* as well as *Syringa,* not found in our material.

The occurrence of pollen of both spruce and larch indicates a temperature of the coldest month ranging from –5 to –2°C. The presence of only *Larix* remains suggests mean temperatures of the warmest month likely to attain +17°C (e.g., Dahl, 1998; Granoszewski, 2003; Kupryjanowicz, 2008), with a minimum mean July temperature of 14°C, as evidenced by the appearance of pollen of *Typha angustifolia* (Kolstrup, 1979). The occurrence of *Betula nana* allows for estimating the maximum temperature of the coldest month as not exceeding 0°C, while the mean annual temperature determined for the taxon varies between –13.4 and 3.7°C (Tobolski, 1991; Granoszewski, 2003; Ballantyne et al., 2010). *Selaginnella selaginoides*, an Arctic-Alpine element, suggests temperatures of the warmest month falling below 17°C (Tobolski, 1991; Zarzycki et al., 2002). Following Mamakowa (1970), a range of 10–14°C should be accepted as the mean June temperature. It is specified to 13°C by the presence of *Myriophyllum verticillatum*.

CHRONOSTRATIGRAPHY

The Weichselian pollen successions so far described for Kraków and southern Poland are represented mostly by tundra and woody tundra vegetation, different from the one recorded in the examined section and generally representing the Weichselian Middle Pleniglacial, particularly the Hengelo and Denekamp interstadials (e.g., Mamakowa and Środoń, 1977; Mamakowa and Rutkowski, 1989a, b).

The obtained results, despite some differences, can be associated with the outcome of studies of plant associations and climatic reconstructions for the close of the Eemian and Early Weichselian interstadials in Eastern, Central and Western Europe (e.g., Behre and Lade, 1986; Bos et al., 2001; Velichko et al., 2005; Kühl et al., 2007; Brewer et al., 2008), including Poland (e.g., Mamakowa, 1989; Bińka and Grzybowski, 2002; Bińka and Nitychoruk, 2003; Granoszewski, 2003; Kupryjanowicz, 2008; Komar et al., 2009; Malkiewicz, 2010; Roman and Balwierz, 2010; Kuszell et al., 2012).

The sections known from Kraków and its immediate surroundings do not provide a continuous record of vegetation development in the Eemian Interglacial and the Early Weichselian. The examined biogenic deposits do not bear such a record either, therefore their chronostratigraphic position is arguable. The absolute age obtained from OSL for detrital sediments found in the upper part of the sections is 53.1 ± 2.5 ka BP (Gd-1394). To some extent, this date is confirmed by the ^{14}C age of the lowest and uppermost layer of biogenic deposits, that appeared to be "infinite" (Gd-15733, >36.3 ka BP; Gd-12730, >37.78 ka BP). As there are no significant differences in the types of vegetation recorded in particular layers of biogenic deposits, they cannot be unequivocally correlated with any of the above-mentioned chronostratigraphic units. Therefore, it is also possible that all peat layers might have been deposited in the same period. However, the presence of three peat layers separated by detrital sediments may suggest that the layers, from the lowest one upwards, represent the close of the Eemian (OIS 5e) and the Brörup and Odderade interstadials, while the detrital sediments correspond to the Herning and Rederstall stadials (OIS 5a–d, Fig. 3). Although cryoturbations developed in the Early Glacial stadials in many places in Germany (e.g., Mol, 1997; Mol et al., 2000; Bos et al., 2001; Kasse et al., 2003), their absence in this site may be a result of a mild climate. The study area is, after all, located a few hundred kilometres south of the described places. However, the doubts regarding the age of the deposits due to the lack of a reference palaeobotanical site for comparison in this part of Poland require further studies.

RIVER DEVELOPMENT AND ENVIRONMENTAL CHANGES

The proposed interpretation of sediment age is supported by the texture of sand. During the Early Weichselian, aeolian activity was low in Western Europe (e.g., Kasse et al., 2003). In Poland, the formation of loess or dunes was not observed, and the low impact of aeolian processes is confirmed by the lack of RM grains (sample no. 8) and minor amounts of EM/RM grains (Fig. 3D). In Western Europe, the Early Weichselian was marked by the occurrence of periglacial phenomena, evidenced by cryoturbations and ice-wedge casts (e.g., Bos et al., 2001; Kasse et al., 2003). Assuming that the small-amplitude folds observed in section A (type 1 according to Vandenberghe, 2007) represent cryoturbations and the lack of ice-wedges casts, it may be concluded that seasonal frost was episodic and relatively shallow in the study area.

During the Late Eemian and Weichselian Early Pleniglacial (OIS 5e–OIS 5a–d), the Prądnik River had a meandering channel pattern. Low-energy (meandering and/or anastomosing) channel patterns controlled by temperate climatic conditions in this period have been reported from many European regions (e.g., Mol, 1997; Huissteden et al., 2001; Zieliński and Goździk, 2001; Kasse et al., 2003; Zieliński, 2007; Sokołowski et al., 2009).

WEICHSELIAN EARLY–MIDDLE PLENIGLACIAL

ENVIRONMENTAL AND CLIMATIC CONDITIONS

Lack of biogenic deposits, high proportion of aeolian grains and the possible presence of involutions in the upper part of the deposits, may indicate climate cooling. A palynological record of vegetation near Kraków, from Polanów Samborzecki (Sandomierz Upland, ca. 140 km NE of Kraków), covering, i.a., vegetational changes until the Weichselian Early Glacial, includes open habitats with infrequent patches of pine-birch open forests. It is clearly dominated by NAP pollen evidencing mean temperatures between –13 and –16°C in the coldest month and between 16.5 and 17.5°C in the warmest month (Komar et al., 2009). Compared with earlier periods, this one was characterized by noticeably lower temperatures of the coldest months.

Climatic conditions may also be indicated by the occurrence of large-scale involutions. Although their origin is still under discussion (cf. Vandenberghe, 1988; Neuwerth et al., 2006; Loon, 2009), their presence together with textural features evidencing frost weathering suggests that they may have developed due to differential frost heave and periglacial loading. They are associated with permafrost and degradation of its top (Huijzer and Isarin, 1997; Kasse et al., 2007; Vandenberghe, 2007; Vliet-Lanoë, 2010). To be formed, they require mean annual air temperatures (MAAT) of –8°C (up to –6°C), however, their development in sandy-silty alternations is likely to suggest a slightly higher MAAT of –4°C (Vandenberghe and Pissart, 1993).

CHRONOSTRATIGRAPHY

Considering the dating of the uppermost segment of the deposits (Gd-1394, 53.1 ± 2.5 ka BP), it may be assumed that sediments forming this part of section B developed in the Weichselian Early Pleniglacial and in the initial phase of the Weichselian Middle Pleniglacial (OIS 4–OIS 3). During the former period (Shalkholz Stadial), entire Western and Central Europe was affected by strong cooling (e.g., Huijzer and Vandenberghe, 1998).

RIVER DEVELOPMENT AND ENVIRONMENTAL CHANGES

Environmental changes are definitely confirmed by features of deposits recorded in the upper part of section B. The Weichselian Early Pleniglacial (OIS 4) was marked by aeolian processes proceeding in the conditions of cold and dry climate in various regions of Poland (Dylik, 1969; Goździk, 1981; Buraczyński, 1994; Dzierżek and Stańczuk, 2006). Strong wind activity was also recorded in Western Europe (Vandenberghe, 1985; Huijzer and Vandenberghe, 1998) and resulted in the formation of fluvio-aeolian deposits (Vandenberghe and Huissteden, 1988; Mol et al., 1993).

The upper part of the alluvial deposits is typified by a noticeable increase in the amount of grains affected by aeolian processing. Grains transported by wind action may have been deposited directly in river channels (Huissteden et al., 2000; Mol et al., 2000; Kasse et al., 2003) or on floodplains (Kotarbiński et al., 2000; Huissteden et al., 2000; Mycielska-Dowgiałło and Woronko, 2001, 2004a, b; Woronko, 2012a). As humid sediments are highly cohesive, such grains could not be reincluded in aeolian transport. Conditions for the development of aeolian processes were particularly advantageous in the winter season (Isarin et al., 1997), mainly due to higher wind velocity than in the summer (Seppälä, 2004) and the release of sand grains from frozen ground in sublimation (McKenna and Neumann, 2004). In conditions of periglacial climate, aeolian material previously deposited in the valley bottom was incorporated into fluvial transport during short-lasting spring melts, remarkably increasing river flows (Kasse et al., 2007). Presently, similar events are observed in the zone of arctic or subarctic climate, e.g. in Alaska, in valley bottoms of snowmelt rivers (Lewkowicz and Young, 1991), Iceland (Moutney and Russell, 2004) and Canada (Good and Bryant, 1985). The results of grain-size analysis indicate that during their transport the deposits were not subjected to rapid deposition but to quite opposite processes of segregation and sorting, as evidenced by the very well-sorted saltation segment (Fig. 3C, D), including minor amounts of grains transported in solid suspension as well as dragged or rolled. However, comparison of the mean grain diameter (M_z) and the degree of sorting (σ_1; Fig. 3) shows that the sediments represent a pattern typical of presently forming active parabolic dunes (Mycielska-Dowgiałło, 1995; Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011; Woronko, 2012a). It indicates that, in the fluvial environment, the sediments were transported over a short distance (Mycielska-Dowgiałło, 1993), in which their textural features, characteristic for the aeolian environment (i.e. grain size), could not be completely removed (Woronko et al., 2013).

In beds disturbed with involutions (Fig. 3 A, D, sample no. 2), sands have a very high content of broken grains (C), occurrence of which may result from intense frost weathering in conditions of frequent freeze-thaw processes (e.g., Kowalkowski and Mycielska-Dowgiałło, 1985; Wright, 2000; Dietzel, 2005; Woronko and Hoch, 2011; Woronko, 2012b). Quartz is a more sensitive mineral to this type of weathering than, e.g., unweathered feldspar (Konishchev, 1982; Konishchev and Rogov, 1993; French and Guglielmin, 2000) due to the presence of gas-liquid inclusions (Rogov, 1982; Konishchev and Rogov, 1993; French and Guglielmin, 2000; Barczuk and Kozłowski, 2004; French, 2007; Woronko, 2012b). During freezing, solution found in the inclusions increases its volume, which results in the breaking of quartz grains. It should be also emphasized that the results of analyses, with later modifications, provide evidence for a change in the source of material in fluvial sediments, from only aeolian (sample no. 3) to originating from various environments. The occurrence of broken grains (C) shows an interruption in the floodplain deposition, lasting long enough to enable the formation of involutions and, first of all, production of broken grains. This event was likely to result from the progressive increase in climate aridity or fluvial down-cutting.

Structural features of deposits forming the upper segments of the section allow for various interpretations, however, to some extent, they suggest a change in the channel pattern towards a braided river, supported e.g., by open plant habitats dominant in the Weichselian Early Pleniglacial. High-energy braided channel patterns were recorded for this period at numerous sites in Europe (Mol et al., 2000). However, the Velyky Lukavets River in the Ukrainian Carpathians Foreland did not change its channel pattern in this period (Sokołowski and Stachowicz-Rybka, 2009). Textural features of the alluvial deposits indicate here that the Prądnik River changed the channel pattern from meandering to braided.The change of channel pattern was preceded by the incision of older deposits. Phases dessections dating for the end of the Early Weichselian and the beginning of the Weichselian Early Pleniglacial or the beginning Weichselian Middle Pleniglacial are recorded in different regions of Europe (e.g., Mol et al., 2000; Huissteden et al., 2001; Sokołowski et al., 2009). The vertical range of the incision is not precisely known, as the upper part of section A has not been examined.

CONCLUSIONS

In this region, the discussed site is the first one including alluvial deposits assigned to the Late Eemian–Weichselian Middle Pleniglacial (MIS 5e–MIS 3).

Fluvial sediments of the Prądnik in Kraków, exposed in a constructional excavation near the Kraków Główny railway station, bear a record of fluctuations in climate and climate-controlled plant associations. The pollen analysis of peat was supplemented by the results of identification of macroscopic plant remains. The Eemian–Early Weichselian (MIS 5e–MIS 5a–d) sedimentation proceeded in the environment of boreal coniferous forests dominated by common pine with a small admixture of *Larix, Pinus cembra, Picea, Betula* and *Populus*. The stands were of high density, however, the communities periodically passed into woody tundra most likely due to an increase in ground humidity. Among the three layers of biogenic deposits (C1, C2 and C3), separated by detrital sediments, the lowest one (C1) was probably deposited in the Late Eemian, while the two others, in the Brörup and Odderade interstadials, respectively, representing the Early Weichselian. However, it cannot be excluded that all of them were deposited in the same warm period. The climatic condition during the sedimentation of peat layers were typified by a moderate climate with mean temperatures of the warmest month likely to attain even +17°C. Mean temperatures of the coldest month were presumably of several degrees below 0°C.

Such conditions supported the existence of meandering channels, filled with fining-upward deposits of point-bars, with lithofacies St and SGt overlain by silt with biogenic deposits (abandoned phase). Straight, inter-meander channel segments included lithofacies Sp.

This sedimentary series is marked by an incision, dated at the close of the Early Weichselian. It is followed by a noticeable cooling of climate in the Weichselian Early Pleniglacial (Shalkholz Stadial), marked in the presence of abundant well-rounded and mat-surface aeolian grains in fluvial deposits. The content of aeolian grains increases upwards in the succession. Simultaneously, the channel pattern had changed. The Prądnik became a braided river. Therefore, the formation of this segment of the Prądnik River generally coincides with the development of European rivers and their response to environmental changes.

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